DENIS-P J1228.2-1547 – A New Benchmark Brown Dwarf

C.G. Tinney

Anglo-Australian Observatory, PO Box 296, Epping. 2121. Australia. email: cgt@aaoepp.aao.gov.au

X. Delfosse and T. Forveille

Observatoire de Grenoble, 414 rue de la Piscine, Domaine Universitaire de S^{t} Martin d'Hères, F-38041 Grenoble, France

ABSTRACT

We present optical spectroscopy of three brown dwarf candidates identified in the first 1% of the DENIS sky survey. Low resolution spectra from 6430–9150 Å show these objects to have similar spectra to the brown dwarf candidate GD 165B. High resolution spectroscopy shows that one of the objects – DENIS-P J1228.2-1547 – has a strong 2.3±0.05 Å equivalent width absorption line of Li I 6708 Å, and is therefore a brown dwarf with mass below 0.065 $M_{\odot}$, and age $\lesssim$ 1.5 Gyr. DENIS-P J1228.2-1547 can now be considered a proto-type for brown dwarfs closer to the hydrogen burning limit than Gl 229B.

Subject headings: stars: low-mass, brown dwarfs

1. Introduction

Claims of brown dwarf discovery have historically been problematic. Numerous objects have been claimed as brown dwarfs or brown dwarf candidates over the last 15 years, but few have been either generally accepted or subsequently confirmed. This situation changed – and in spectacular fashion – with the discovery of the brown dwarf Gl 229B (Nakajima et al. 1995). Here at last was a brown dwarf proto-type so cool, and of such low luminosity, that it quickly became universally accepted. Unfortunately, what Gl 229B didn't resolve was the status of more massive brown dwarf candidates.

For example, the nature of GD 165B – the next best old brown dwarf candidate – remains unclear (Becklin & Zuckerman 1988; Kirkpatrick 1997a). Although its optical spectrum is qualitatively different from that of low-mass stars (Kirkpatrick, Henry & Liebert 1993; Kirkpatrick, Beichman & Skrutskie 1997), its infrared spectrum is not (Jones et al. 1994). And unfortunately, the closeness of its white dwarf companion makes the detection of Li almost impossible. Thackrah, Jones, & Hawkins (1997) have found a likely field brown dwarf (296A), but it is of *very* early spectral type (M5.5), indicating an age of less than 200 Myr. There is a need for a late proto-type object near the star-to-brown-dwarf transition, but which is *clearly* a brown dwarf, against which objects like GD 165B can be compared. We present here observations of just such an object, DENIS-P J1228.2-1547, discovered in the first ∼1% of data examined from the Deep Near Infrared Southern sky survey (DENIS).

2. Observations

The DENIS survey will cover the entire southern sky in three infrared pass bands to 3-σ limits of I=18.5, J=16.5, K′=13.5 (Epchtein 1997; Copet et al. 1997). Such a survey is ideally suited to finding field brown dwarfs. The DENIS mini-survey project (Delfosse et al. 1997; Delfosse, Tinney & Forveille 1997) has begun this search by observing brown dwarf candidates from the first ∼1% (230 □°) of the initial DENIS data. Infrared spectroscopy obtained on the 3.9m Anglo-Australian Telescope (AAT) confirmed that at least three of the mini-survey objects were as cool, or cooler than, GD 165B (Delfosse et al. 1997).

Optical spectroscopy was obtained with the AAT on 1997 June 7-9 (UT), using the RGO Spectrograph with TEK 1K CCD#2. Observations were made using both a 270R grating in blaze-to-camera mode, providing a resolution of 7 Å and a wavelength coverage of 6425–9800 Å, and a 1200R grating in blaze-to-collimator mode giving a resolution of 1 Å and a wavelength coverage of 6495–7030 Å. The latter set-up was specifically chosen to permit observation of both the Hα and Li I 6708 Å lines. All three DENIS objects of interest, as well as several very low-mass stars were observed. The observations are summarised in Table 1. Finding charts for the three DENIS objects can be found in Delfosse et al. (1997). These data were processed using standard techniques within the FIGARO data reduction package (Shortridge 1993).

3. Discussion

The resulting spectra are shown in Figure 1 (the low resolution spectra) and Figure 2 (the high resolution spectra). Perhaps the most instantly noticeable feature of Figure 1 is the remarkable similarity between the spectra of the three DENIS objects and the spectra of GD 165B – for so long seen as a singleton object which fits into no classification scheme (Kirkpatrick et al. 1997; Kirkpatrick et al. 1993).

3.1. Low-resolution spectra

The spectra in Figure 1 have been organised in their apparent order of spectral type – latest towards the top. Because of the strength of terrestrial H_2O, the spectra are not plotted beyond 9150 Å. The spectral types shown for VB 10, BRI 0021-0214 and GD 165B are due to Kirkpatrick et al. (1997) – the other types are our estimates. Prominent in the spectra are the lines of Cs I at 8521 Å and 8943 Å. These lines were pointed out in the spectra of very low-mass stars by Tinney (1997), at equivalent widths (EW) of 0.5-1 Å. In the latest of the DENIS objects (DENIS-P J1228.2-1547 and DENIS-P J0205.4-1159) they are present at a whopping EW=6.5 Å[1]. Also strong are lines of Rb I at 7800 Å and 7943 Å (Basri & Marcy 1995; Tinney 1997). Interestingly the lines of Na I and K I, so prominent in late M-dwarfs, seem to become progressively weaker beyond M10.

[1] Whenever equivalent widths are referred to they are always the "psuedo-equivalent width" defined by the apparent continua available near the lines, at the resolution of the observations. In practice, no part of the spectrum of these objects is free of molecular absorption, so no absolute continuum is ever available.

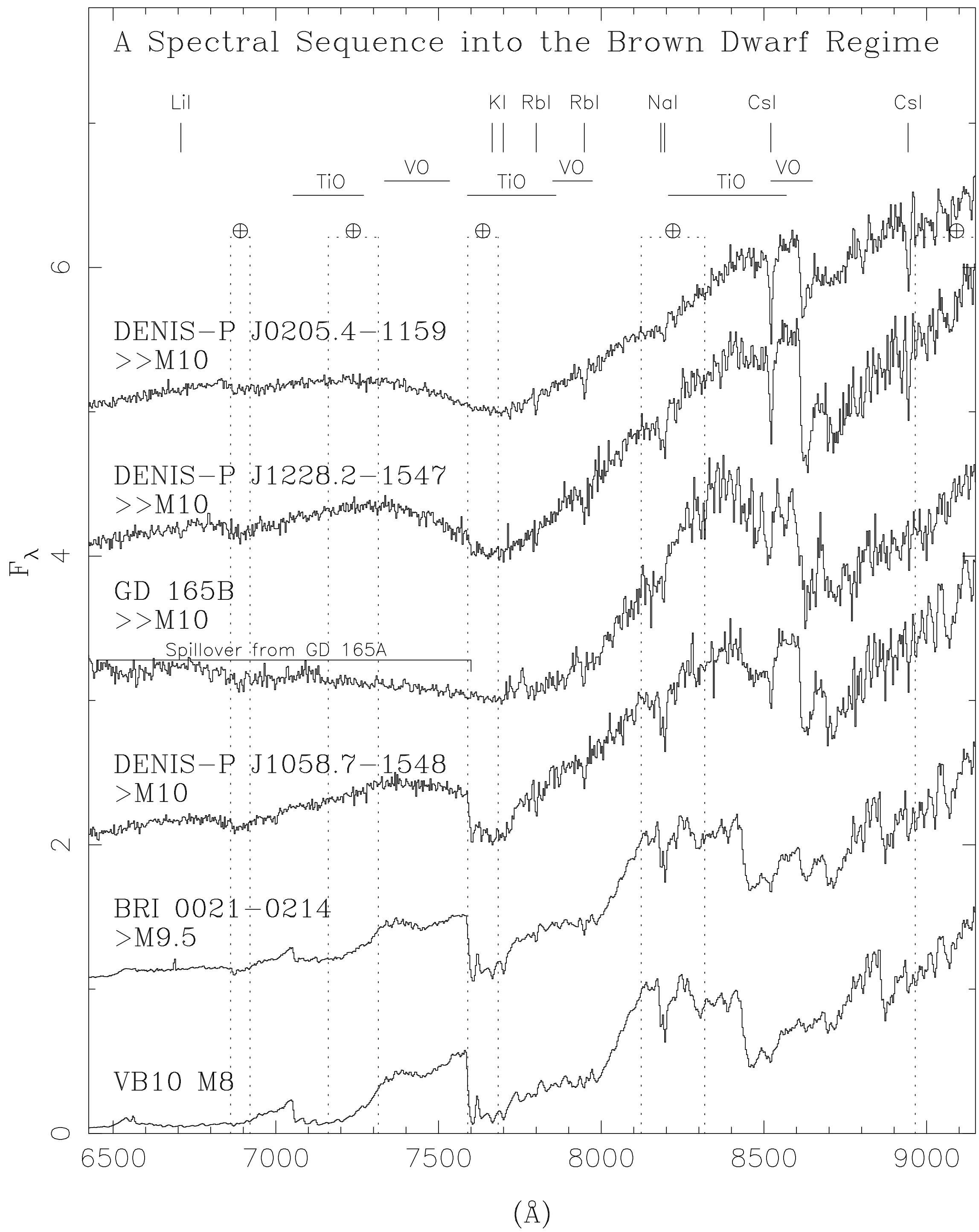

Fig. 1.— Low resolution (7 Å) AAT spectra of the DENIS brown dwarf candidates (and two comparison spectra) arranged in approximate order of spectral lateness, together with the GD 165B spectrum of Kirkpatrick et al. (1993), which is subject to contamination below 7600 Å. Each spectrum has been normalised to unity at 8800 Å, and offset in unit steps for clarity. The spectral types shown are those due to Kirkpatrick et al. (1997), or our estimates on their system. Stellar atomic and molecular absorption features are marked, as are terrestrial absorption features, which have not been corrected.

Table 1
Observation Log.

Object	Position[a] (J2000.0)	270R Exp. (s)	1200R Exp. (s)
DENIS-P J1228.2-1547	12:28:13.8 −15:47:11	1800	18000
DENIS-P J1058.7-1548	10:58:46.5 −15:48:00	3600	7200
DENIS-P J0205.4-1159	02:05:29.0 −11:59:25	5400	–
BRI 0021-0214	00:24:24.6 −01:58:22	1800	1800
VB 10/LHS 474	19:16:57.9 +05:09:10	600	–

[a]Positions for the DENIS objects are from Delfosse et al. 1997, those for the remainder are from Tinney et al. 1995. The DENIS-P prefix indicates that these are provisional DENIS objects, which have not been produced by the final DENIS catalogue pipeline.

However, the strongest feature of Figure 1 is the almost counter-intuitive weakening of the TiO and VO molecular bands with decreasing temperature. This is primarily due to the formation of dust, which plays an important role in these very late atmospheres. This is both because of its influence on opacities (eg. models require opacity due to dust to match the spectral energy distribution of GD 165B – Tsuji et al. 1996) *and* composition (eg. the formation of perovskite, $CaTiO_3$, will deplete atmospheres at $\sim$ 1600K of their TiO, causing these bands to vanish – Allard 1997; Kirkpatrick 1997a). Notice in particular the bands near 8500 Å which are weakly present in GD 165B, but have vanished at the temperatures of DENIS-P J1228.2-1547 and DENIS-P J0205.4-1159.

The spectra confirm the result of Delfosse et al. (1997) – these three objects have effective temperatures similar to, or cooler than, GD 165B. Like GD 165B, the three DENIS objects all show weak, or non-existent, TiO and VO bands, as well as strong lines of Cs I (Kirkpatrick 1997b). In fact, apart from being very red, their spectra look almost nothing like those of late M dwarfs. This supports the suggestion of Kirkpatrick (1997a) that an entirely new spectral type is required for this class of objects – based on features like the absence of TiO and VO, and the strength of Cs I.

3.2. Lithium Spectra

Figure 2 shows the high resolution spectra obtained for DENIS-P J1228.2-1547 and DENIS-P J1058.7-1548, as well as a comparison spectrum of BRI 0021-0214,

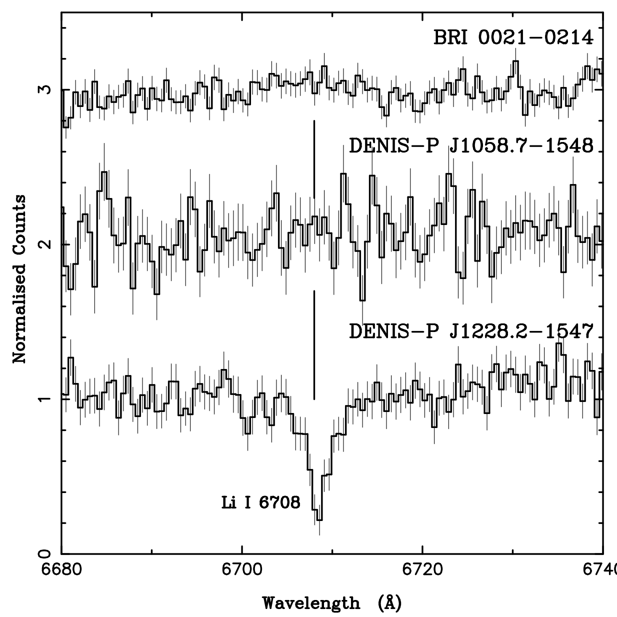

Fig. 2.— High resolution (1 Å) AAT spectra in the region of the Li I 6708 Å line. Each spectrum has been normalised to unity at 6660-6680 Å, and offset in unit steps for clarity. Error bars show the propogated photon-counting uncertainties.

which is known to have depleted its lithium (Basri & Marcy 1995). DENIS-P J1228.2-1547 shows a clear Li absorption feature with EW=2.30±0.05 Å. (The quoted uncertainty is based on photon-counting errors, and does not include the systematic uncertainty in the "pseudo" equivalent width.) Despite the fact that DENIS-P J1058.7-1548 was observed for only 2 hours (as compared to 5 hours for DENIS-P J1228.2-1547) it clearly *does not* show a Li absorption of a similar strength. We place a $3-\sigma$ upper limit on this object of EW<0.5 Å.

Interpretation of these equivalent widths as Li abundances is made problematic by the lack of published model atmospheres at the required spectral resolution and temperatures. However, based on the models and curves of growth of Pavlenko et al. (1995) which extend to 2000K, we crudely estimate [Li/H] = ∼ 1–3. Delfosse et al. (1997) estimate absolute magnitudes for DENIS-P J1228.2-1547 and DENIS-P J1058.7-1548 of $M_K = 12.1 \pm 0.4$ and 11.4 ± 0.4 (respectively). These seem to be confirmed by the Fig. 1 spectra, which show DENIS-P J1058.7-1548 being of earlier type than GD 165B ($M_K = 11.7 \pm 0.2$; Dahn 1997; Tinney, Mould & Reid 1993), and DENIS-P J1228.2-1547 being of later type. Bolometric corrections have been estimated for only one object at these temperatures (GD 165B, Tinney, Mould & Reid 1993), however the unceratinties in BC_K are, in any case, considerably smaller than those in M_K. We derive $M_{bol} = 15.4 \pm 0.5$ and 14.7 ± 0.5, or $\log(L/L_\odot) = -4.3$ and -4.0. At $\log(L/L_\odot) = -4.3$, the presence of *any lithium at all* in DENIS-P J1228.2-1547 constrains the mass to be less than $0.065\,M_\odot$, and the age to be $\lesssim 1$ Gyr (Nelson, Rappaport & Chiang 1993). It is clearly a *bona fide* brown dwarf – it cannot be a more massive object which has not yet depleted its lithium, since it is more than 10 times fainter than models at the required age (∼ 100 Myr). Conversely, DENIS-P J1058.7-1548 must be more massive than $0.065\,M_\odot$.

Recently, an improved understanding of convection in cool atmospheres has found that for $T_{eff} \leq 2200$K, the central convection zone does *not* reach into the photosphere (Allard 1997). This lead Allard to suggest that the "Li test" is inappropriate for M10 dwarfs and later. While this is true, objects more massive than $0.05\,M_\odot$ will spend at least $\approx 3 \times 10^8$ yr at $T_{eff} \geq 2300$K (Chabrier, Baraffe & Plez 1996; Burrows et al. 1993), during which time their Li will be depleted if central temperatures are high enough (ie if their mass is $\geq 0.065\,M_\odot$), and will not be depleted if their mass is $\leq 0.065\,M_\odot$. For objects less massive than $0.05\,M_\odot$ the presence of Li will reflect both the initial Li abundance, and the timescale at which the convective interior drops below the photosphere. In either case, the presence of Li in DENIS-P J1228.2-1547 must imply a brown dwarf nature, since Li would have been totally depleted in an object with its luminosity were it more massive than $0.065\,M_\odot$.

3.3. Hα emission

Interestingly, only one of the DENIS objects reported here shows evidence for Hα emission – and that is very weak. Our high resolution spectra show Hα emission with EW=1.3±0.4 Å in DENIS-P J1058.7-1548. We place 3-σ upper limits on emission in DENIS-P J1228.2-1547 and DENIS-P J0205.4-1159 of 1.0 Å and 3.5 Å, respectively. The level of emission in these, presumably old, dwarfs is significantly less than that seen in the Pleiades brown dwarfs (age ∼ 100 Myr, EW≈5 Å Rebolo et al. 1996). In particular, this implies that DENIS-P J1228.2-1547 probably has an age $\gtrsim 100$ Myr. Given its luminosity, this imposes a lower mass limit of about $0.02\,M_\odot$(Burrows et al. 1993).

We also detect Hα emission at a level of 1.30±0.05 Å in BRI 0021-0214, in which Hα had not previously been detected (Basri, Marcy & Graham 1996). This clearly indicates that chromospheric activity *is* present in this star, though at a low level.

4. Conclusions

Finally a brown dwarf has been discovered, just below the brown dwarf limit, conclusively showing us what a brown dwarf of $\lesssim 0.065\,M_\odot$ looks like. The similarity of the optical and infrared spectra of DENIS-P J1228.2-1547 to that of GD 165B, and the other two DENIS objects presented here, suggests that they too probably lie below the brown dwarf limit. In fact, the available data point to DENIS-P J0205.4-1159 being *cooler* than DENIS-P J1228.2-1547 – Li observations of this object will be made a high priority. Lastly, it is worth emphasising that these three dwarfs were discovered in just the first ∼1% of the DENIS data – many more exciting results can be expected in the future as this survey continues.

We are grateful to Davy Kirkpatrick for discussions on his unpublished GD 165B data and for a thorough

referee's report, and to Ben Oppenheimer for helpful discussions about his unpublished Gl 229B data. We are also extremely grateful to the AAO Director, Brian Boyle, for providing the discretionary time in which these observations were carried out. CGT would personally like to thank Nicolas Epchtein and the members of the DENIS team for providing access to DENIS data prior to its general release. The DENIS project is partly funded by the European Commission through the *SCIENCE* and *HCM* grants. It is also supported, in France by INSU, the Education Minsitry and CNRS; in Germany by the Land of Baden-Würtenburg; in Spain by DGICYT; in Italy by CNR; in Austria by the FFWF and BWF; in Brazil by FAPESP; and in Hungary by an OTKA grant. It is also partly supported by an ESO C&EE grant.

REFERENCES

Allard, F. 1997, in "Brown Dwarfs and Extra-solar Planets", A.S.P. Conference Series, eds. Rebolo, R., Martín, E. & Zapatero Osorio, M.

Becklin E. E., Zuckerman, B. 1988, Nature, 336, 656

Basri, G. & Marcy, G. W. 1995, AJ, 109, 762

Basri, G., Marcy, G. W. & Graham, J.R. 1996, ApJ, 458, 600

Burrows, A., Hubbard, W. B., Saumon, D. & Lunine, J. I. 1993, ApJ, 406, 158

Copet, E. et al. 1997, A&A, submitted

Chabrier, G., Baraffe, I. & Plez, B. 1996, ApJ, 459, L91

Dahn, C. 1997, private communication

Delfosse, X. etal. 1997, A&A, submitted

Delfosse, X., Tinney, C. G., Forveille, F. 1997, in preparation

Epchtein, N. 1997, in "The Impact of Large Scale Near-infrared Surveys", ed. F. Garzon, N. Epchtein, A. Omont, W. B. Burton, P. Persi Kluwer: Dordrecht

Jones H. R. A., Longmore, A. J., Jameson, R. F., Mountain, C. M. 1994, MNRAS, 267, 413

Kirkpatrick, J. D. 1997a, in "Brown Dwarfs and Extra-solar Planets", A.S.P. Conference Series, eds. Rebolo, R., Martín, E. & Zapatero Osorio, M., in press

Kirkpatrick, J. D. 1997b, private communication

Kirkpatrick, J. D., Beichman, C. A. & Skrutskie, M. F. 1997, ApJ, 476, 311

Kirkpatrick, J. D., Henry, T. J. & Liebert, J. 1993, ApJ, 406, 701

Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimovski, D. A., Matthews, K., Durrance, S. T. 1995, Nature, 378, 463

Nelson, L. A., Rappaport, S., Chiang, E. 1993, ApJ, 413, 364

Pavlenko, Y. V., Rebolo, R., Martín, E. L., García López, R. J. 1995, A&A, 303, 807

Rebolo, R., Martín, E. L., Basri, G., Marcy, G. W., Zapatero-Osorio, M. R. 1996, ApJ, 469, L53

Shortridge, K. 1993, in "Astronomical Data Analysis Software and Systems II", A.S.P. Conference Series, Vol. 52, 1993, p. 219

Tsuji, T., Ohnaka, K., Aoki, W. & Nakajima, T. 1996, A&A, 308, L29

Thackrah, A., Jones, H. & Hawkins, M. 1997, MNRAS, 284, 507

Tinney, C. G., Mould, J. R. & Reid, I. N. 1993, AJ, 105, 1045

Tinney, C.G. 1997, in "Brown Dwarfs and Extra-solar Planets", A.S.P. Conference Series, eds. Rebolo, R., Martín, E. & Zapatero Osorio, M., in press

Tinney, C. G., Reid, I. N., Gizis, J., Mould, J. R. 1995, AJ, 110, 3014

This 2-column preprint was prepared with the AAS LaTeX macros v4.0.